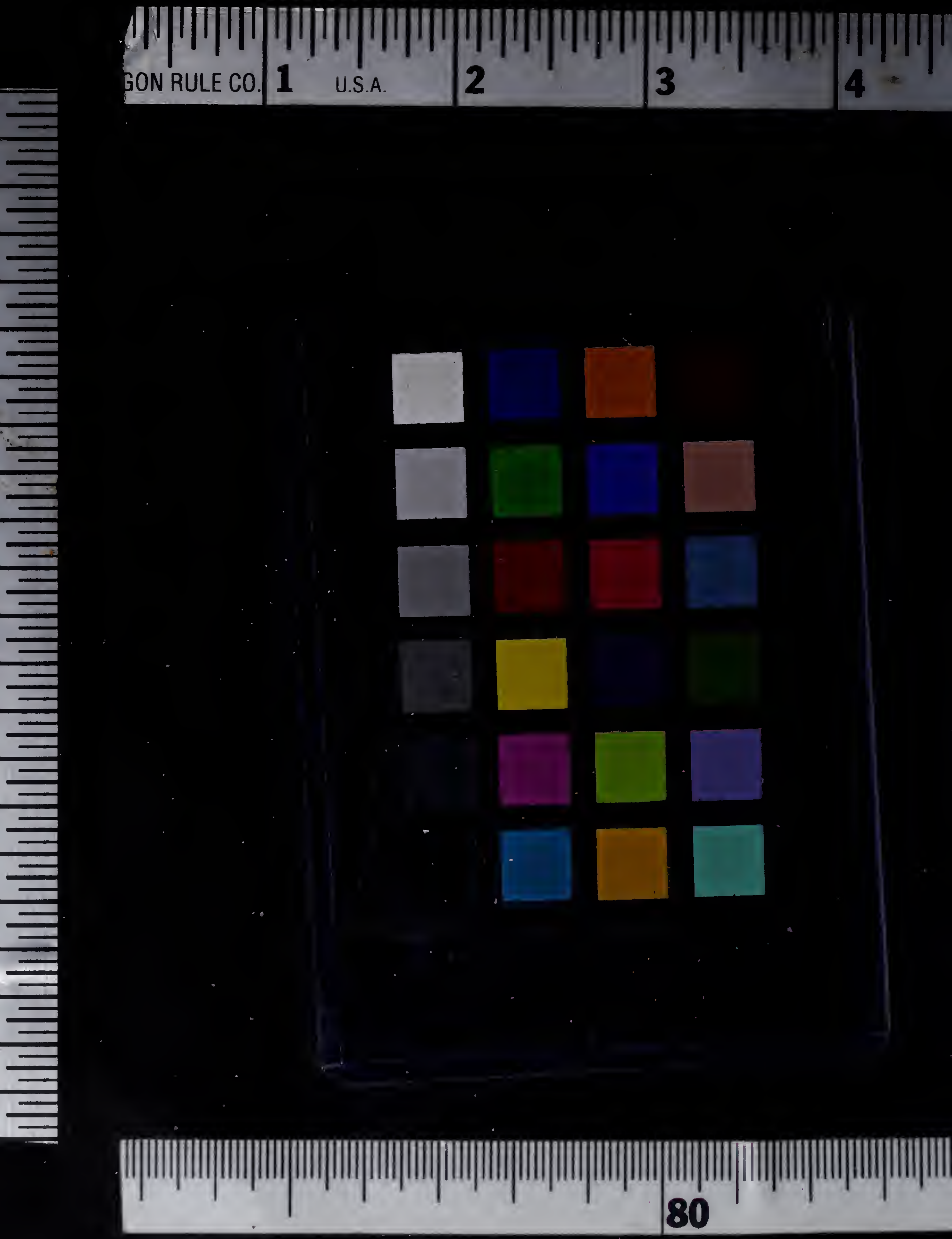
pavement rather suddenly stops, and the course of the brook is through a narrow grassy flat, which soon broadens out into a broad swamp at the junction of the two headwater forks. The absence of boulders and blocks along the brook just up-stream may be largely or wholly due to the construction of a private road across the brook about 300 feet east of the highway, — the rocks having been collected for its construction. Where the northern of these two brooklets crosses the road, one finds on the west side of the road, going up-stream, a few bare ledges and many blocks, including some large boulders, and beyond these the flat swampy ground already mentioned as the source of the brooklets. The elevation at the road at this point is 165 feet (aneroid). Going down-stream from the road, one finds a pretty continuous boulder pavement as far as the broad meadow at the junction of the two brooklets, though the boulders are much thicker in some places than in others. There are a few bare ledges here, also.

On both these brooklets the boulder pavement is a distinct and striking feature. There is no such abundance of blocks on the slopes which lead away from the brooks to the north and south. The distribution is emphatically along the two lines of lowest ground; and the width of the pavement together with the general good size of the boulders seems to indicate that scouring much stronger than that of the present little stream has gone on in the past, washing the finer parts of the thin till cover down-stream, and leaving bare ledges and a thick pavement of boulders. There are no steep banks, however, enclosing the paved zone, such as one might expect to find.

Down-stream from the junction, the brook follows generally a rather broad flat meadow; and though boulders may once have been plentiful at certain points along its course, there is no longer anything like the boulder pavement seen up-stream. From the railroad for about 500 feet southward along the brook, however, there are a good many boulders, possibly of some significance. Below this the valley becomes extremely broad, flat, and swampy. These flat meadows along the brook are evidently aggraded parts of its valley; and they may have been built up by the supply of gravels and fine material from the scoured boulder-paved pass up-stream.

Along the course of Stony Brook, in several places, particularly between Kendal Green and Roberts, there are stretches of boulder pavement similar to those just described. Doubtless the brook gets its name from this fact. Moreover, the two large pot-holes beside the railroad embankment, near the northern end of Stony Brook Reservoir, may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AT HARVARD COLLEGE.
Vol. XLII.

GEOLOGICAL SERIES, Vol. VI. No. 6.

THE SAND PLAINS OF GLACIAL LAKE SUDBURY.

By James Walter Goldthwait.

With Five Plates.

CAMBRIDGE, MASS., U.S.A.:
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Introduction.

ALTHOUGH sand plains have received much attention from geologists in New England, it is only of recent years that the grouping of these deltas and their relative altitudes have been studied in a detailed way, with the purpose of tracing the history of the ice-front lakes in which they were built. The work done by Professors Crosby and Grabau, and by Dr. Clapp, has shown the possibilities offered by such a study. During the academic year 1903–1904, as a graduate student under Prof. W. M. Davis of Harvard University, I undertook a study of the sand plains of the Sudbury valley, twenty miles west of Boston. My purpose was to investigate the grouping of sand plains in a single drainage basin, with greater accuracy in the determination of levels than had hitherto been attempted. The chief result of the work, as will be seen, was the discovery that the sand plains of this district do not conform to the horizontal step scheme of grouping used by Crosby and others for the neighboring extinct lakes Nashua, Charles, and Bouvé; but that they seem rather to record a postglacial tilt, by which their original relations of level have been upset.

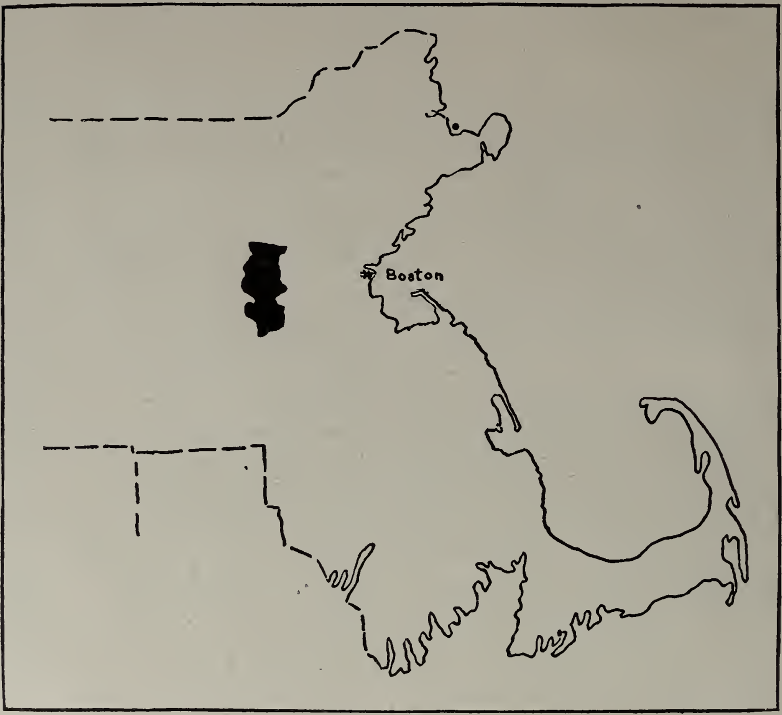

Figure 1.

Sketch map of eastern Massachusetts showing location of Lake Sudbury.

I shall first review the conditions under which temporary glacial lakes might form, and the probable history they would undergo; passing then to those physiographic features which mark extinct ice-front lakes, especially sand plains, I shall consider the horizontal step scheme of arrangement of deltas used by Professor Crosby and others; and finally, applying this scheme to the data from the Sudbury valley, I shall show that the sand plains of Lake Sudbury do not fall into flat steps, but probably into a tilted step-system.

Conditions of Drainage along the Front of the Retreating Ice-Sheet.

When the ice-sheet melted back over New England, uncovering a land surface of gentle irregularity, the country along its front must have met with temporary conditions of drainage quite unlike those of the present day. The ice must have blocked the courses of many streams, turning them one side or damming them up to form temporary lakes. The melting of the ice itself doubtless contributed in a measure to the volume of the streams in front of it, although the rate of melting may have been so slow that there was only a moderate flooding of the streams.

Where the ice-sheet lay with its front along a divide between two stream systems, or on ground that sloped away from it, there was opportunity in a given time for either an unusual amount of erosion or an unusual amount of deposition. Each stream that drained away from the ice would from the beginning attempt to make an evenly graded bed for itself, either degrading or aggrading according to the conditions of load, volume, and slope: the greater the supply of waste, the stronger the tendency to aggrade; the steeper the slope, the greater the power to erode. An ice-fed stream which was given little waste to carry, and which ran down a steep slope, would be very active in eroding, while another stream which received an abundance of waste gravels, and which ran down a gentle slope, would be active in aggrading. In the first case, the resulting physiographic feature might be a slope or a channel swept clean of all but boulders, coarse gravel, and bed-rock ledges; in the last, it might be an alluvial fan or a waste-filled valley.

As soon as the ice had melted back of a divide, so that its front lay across the lower part of a valley, it enclosed a basin whose margin was in part the ice-wall and in part the high ground which formed the watershed of the valley. Inasmuch as each of these basins was originally covered by the ice-sheet, and was uncovered by its melting off, each must always have contained water up to as high a level as the lowest point on its rim; for each of these low points, or "cols," would have served as an outlet to drain off the excess of water in the adjoining basin. Besides the water derived from the melting ice, whatever water was shed into the basin by ordinary process of rainfall must have aided in keeping it filled to its capacity.

I propose now to trace the steps which an ice-front lake of this sort might be expected to pass through as the ice retreated.

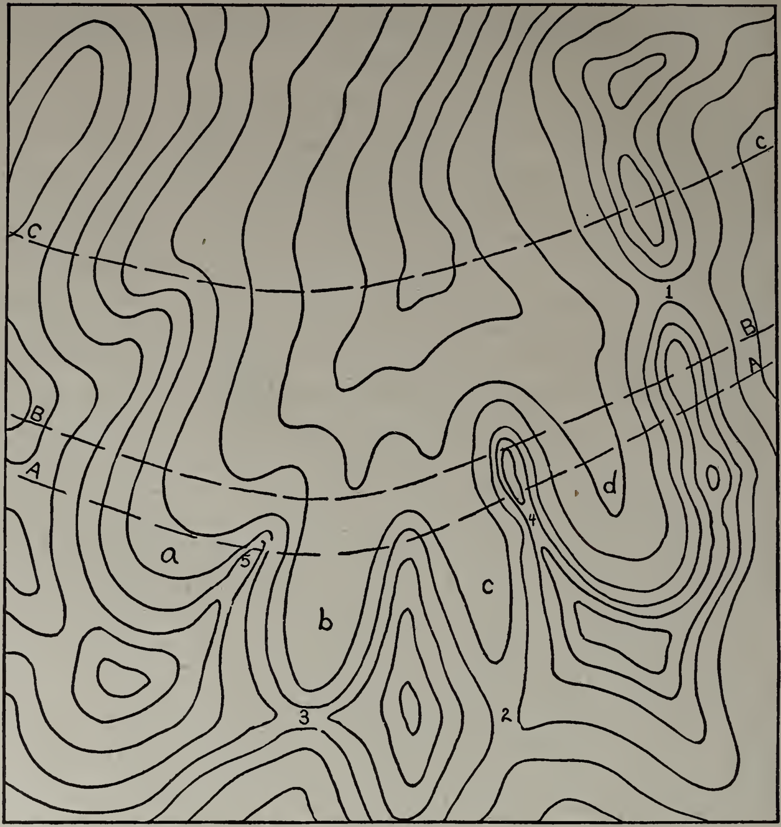

FIGURE 2.

Diagrammatic contour map to show developmental changes in a temporary ice-front lake.

Life History of a Temporary Ice-Front Lake.

When the ice stands just back of a divide, it will form many little lakes at different levels. From the fact that valleys branch and re-branch headwards so that the number of little valleys is greatest near the divide, it follows that the closer the ice-wall is to the divide, the more little valleys it will shut in, and the more little lakelets there will be. Since also it is probable that the cols at the heads of these little valleys have different altitudes, the lakelets formed at this stage of ice-retreat will not only be many in number, but will have different levels. Thus in the diagram (Fig. 2) the ice standing with its front at A . . A, north of the divide, shuts in four lakelets at different levels, indicated by the figures 2, 3, 4, 5. Lakelets *b* and *c* overflow across the main divide through cols which have altitudes 3 and 2 respectively. It may happen, however, that a lakelet finds its lowest outlet through a col in a secondary divide into an adjacent lakelet or across a secondary divide directly at the ice-front. The latter is notably the case in the temporary ice-front lakes of western New York, described by Fairchild (a, b, c, d, e, f). In the diagram, lakelet *d* drains westward into *c*, through a col 4 in the secondary divide which separates these two lakelets; also, lakelet *a* flows eastward into *b*, across the dividing spur directly at the ice-front, at the level 5. Many small lakelets, then, at different levels, characterize the first stages of withdrawal of the ice from a divide.

As the ice-front melts back, it will retreat beyond the junction of certain of the smaller headwater valleys, so that the separate lakelets originally shut in, in those valleys, will merge into a single lake. Thus, in the figure, when the ice has withdrawn to B . . B, lakelets *b* and *c* will coalesce. As the two lakelets unite, the higher one will drain down to the level of the lower, leaving its old outlet high and dry. At the moment of coalescence, the submerged area will of course be equal to the sum of the two original lakelets; but as the level of the higher one falls, the submerged area is partly reduced in extent, in a measure depending on the amount by which the higher lakelet is lowered, and its shallowness. Thus in the figure, when at stage B . . B lakelets *b* and *c* unite, the level of *b* will fall from 3 to 2, the old outlet at 3 being abandoned, and its shore-line will contract to fit the lower contour. Still, under ordinary conditions, the lake of coalescence will be larger than either of the two original lakelets, for it contains all of one and part of the other. If, however, the outlet of the lake of coalescence is below the level of the bottom of the higher lakelet, it will drain the lakelet dry, and the lake of coalescence will then be no larger than the original lakelet was at the time the two united. In the figure, the total disappearance of a lakelet, due to coalescence with a much lower one, is shown by lakelet *a*, which between stages A . . A and B . . B falls from level 5 to assume the level of the lake of coalescence, which is 3, and later 2, draining dry, however, because the new level 2 is below its lakelet bottom. Early in the withdrawal of the ice from the divide, then, there is a coalescence of the many original lakelets into a smaller number of larger lakes; some lakelets are wholly drained off. Lakes increase in size, and decrease in number. At the same time, they come more nearly into an agreement of level, the higher levels being abandoned for the lower.

Besides this merging into larger lakes, as the ice retreats from a divide, characteristic of early stages, there soon begins a succession of lowerings of level, brought about by the uncovering of lower cols in the rim of the basin. Each time a lower col is uncovered, a new outlet is formed, and the lake-level falls accordingly. So while the lakes are gaining steadily in area, during the withdrawal of the ice boundary, they are always liable to a loss in area through the lowering of the water-level to fit a new outlet. Thus in the diagram, by the retreat of the ice-front from B . . B to C . . C, the lake gains in area; but since during the retreat a lower col has been uncovered, at level 1, the water-level of the lake has fallen, and there has been a consequent loss in area. In this case, the gain through withdrawal has been greater than the loss by lowering of level. With continued withdrawal, then, there are both gains and losses in area, and successive lowerings of water-level to fit new outlets.

Changes of this sort will go on in the ice-dammed lake until at last the ice abandons the basin and allows the natural drainage to take its place.

Factors which control the Stability of Ice-Front Lakes.

The slower the rate of withdrawal of the ice-front, the longer will the lakes maintain their level and their form; for it is through withdrawal that new outlets are opened and lowerings of level are brought about. The distance from an active col outlet to the next lower one, which will replace it in draining off the water, also controls in part the permanence of form and level of the lake. Again, the strength of material over which the overflow takes place — whether it be till or bed-rock — will affect the permanence of level of the lake, and therefore its form; for if an outlet is actively cutting down its bed, it is lowering the level of the lake which it drains.

The permanence of lake-levels is of great consequence to us, for on it depends the degree of development of all those features which bear record of the lake's history. The longer a water-level is maintained, the greater and the more perfect will be the development of lake-shore forms and deltas, and the more data will be accessible for reconstructing the water-planes which they mark.

Physiographic Features which mark Water-Planes in an Ice-Front Lake.

The features which one may look for as evidence of an extinct ice-front lake are briefly these: —

(*a*) SHORE-LINES, marked by beaches and bars, or by escarpments and benches, built by the waves of the lake wherever the material is non-resistant enough, the exposure great enough, and the level of the lake permanent enough. Benches and bars of this sort are wonderfully well developed along the shores of the great lakes of the ice age, like Bonneville and Agassiz; they are easily traced along the shores of Lakes Chicago, Algonquin, Warren and Iroquois; and they are fairly well shown in New England in the Contocook valley near Hillsboro, N. H.

(*b*) OUTLET CHANNELS, cut across cols or spurs by overflowing waters, wherever the material was weak enough and the outlet was maintained long enough. The remarkable dry gorges of Lake Warren, near Syracuse, N. Y., are fine examples of outlet channels (Fairchild; a, b, c, d, e, f). Another is the valley of the Illinois River, cut by the outlet of Lake Chicago.

(*c*) LAKE BOTTOM DEPOSITS. The finer clays and silts which are fed into the lake will be carried far out, and may settle to form a horizontally stratified deposit. Silt deposits of this nature have been described by Upham in his accounts of glacial Lake Agassiz (d, 20–25).

(*d*) DELTAS. Wherever a stream enters one of these lakes, there is opportunity for a delta to form, provided the supply of waste is too rapid or too coarse for the waves of the lake to wash it away, and provided there is time enough. These deltas are large features in Lake Agassiz (Upham; a, d); and in the New York lakes described by Fairchild fine deltas were built where outlets from one lake entered the next (Fairchild; e, 38, 39, 52, 59).

(*e*) SAND DELTAS, or SAND PLAINS. These are deltas of a special class, and of such importance in New England that they deserve separate treatment. A brief description and discussion of them follows.

Sand Plains — their Form and Structure.

Sand plains are delta-like deposits of sand and gravel, built out from the ice into standing water at its front. The fact that gravels swept out from the melting ice occur thus, in isolated patches, rather than in a vaguely continuous sheet over the whole region, indicates that the drainage near the edge of the ice-sheet was systematic enough to allow the concentration of waste at occasional favorable points along its front.

In their broader features of form and structure, sand plains resemble deltas built under ordinary conditions, by streams entering a body of standing water. Like normal deltas, they have a nearly flat, gently sloping surface, the "top slope," and an outer or free border, the "front slope," which slants more decidedly and is lobate in form; in composition, the material becomes noticeably finer towards the free border; in structure, the sand plains show inclined beds below with horizontal beds of coarser material above. Yet while sand plains are delta-like in these respects, the peculiar conditions under which they are built give them certain very definite characteristics not common to ordinary deltas. Instead of being fan-shaped deposits built out from lake-shores by single streams, sand plains are more often semi-elliptical in outline, as if built out continuously from the ice for some distance along its front by many streams. In fact, they are most irregular in plan.

The headward border of a sand plain, moreover, is not the lake-shore border of a common delta, but an "ice-contact" or "back slope," which marks the position of the ice-front against which the gravels were laid down. Inasmuch as the back slope shows exactly where the ice-front was when the sand plain was built, it is a great help in determining the ice boundary of the ice-front lake at that time. In linear extent the back slope is straight or irregular, according as the ice-front was straight or irregular. In surface form it may be a simple straight slope of from 30 to 45 degrees, — the natural slope or "angle of repose" assumed by the gravels when their ice support was removed by melting. It is frequently broken, however, by hollows or kettle-holes, where isolated blocks of ice were enclosed in the gravel, and occasionally the ice-margin of a plain is wholly a belt of knobs and kettles, indicating an irregular ice-front where deposition took place among ice-blocks or upon a thin irregular ice-margin. In some cases, also, the ice-border is marked by a high moraine which rises above the surface of the plain, and is bounded on the back by the usual steep ice-contact slope. More typically, however, the back slope meets the top slope of the sand plain at a sharp angle or shoulder. At the back of the plain the material is coarsest, — usually cobbly gravel with boulders, which have reached the ground either by tumbling or melting from the ice.

The top slope is often so flat as to appear like a level plain; but usually there is a perceptible slope, 3 to 5 degrees, from the ice-border towards the free border. Near the back of the plain, kettle-holes are common, forming depressions in the top slope; near its front the plain is flattest, often unbroken save for shallow depressions which lead down to interlobate hollows, and which seem to indicate partial scouring, subsequent to the building of the plain. Cross-sections through the body of the plain generally show a decrease in size of material towards the front, with also a decrease in thickness of the topset beds.

The front slope, in cases where lobes are well developed, meets the top slope at a low obtuse angle, forming the "brow" of the lobes. This point is important, because it indicates the level of the water in which the delta was built, the flat above the brow being almost wholly of subaerial construction and the front slope sub-aqueous. Often, however, the development of lobes is imperfect, or even entirely wanting, on account of the shallowness of the lake, the irregularity of its bottom, or to the building forward of the plain to meet the shore or an ice-border.

Eskers.

Associated with these ice-bound delta deposits are usually ridges of gravel, eskers, which mark the courses of streams that fed the deltas. That these are often subglacial deposits is now recognized by most geologists. They concern our problem chiefly in so far as their position shows an area covered by the ice at the time they were formed, as their general direction indicates the general direction of the ice-front, being naturally perpendicular to it, and as their maximum height shows approximately the maximum height of deltas for the same stage of lake level. For a good description of sand plains and eskers, see Grabau (565–567, 574–578).

Significance of Sand Plains.

In what ways do sand plains, singly and collectively, throw light on the history of the retreat of the ice-sheet?

In the first place, their ice-contact borders give exact locations of the ice-front at the stages they represent. Taking a single sand plain, one can of course reconstruct only a small fragment of ice-front, and can hardly get a fair idea of the whole ice-dam; but by locating and mapping the back slopes of all the sand plains in an extinct lake basin, the fragmentary evidence may be found to fall into so systematic a scheme that it is possible to reconstruct with some accuracy successive lines of ice-front clear across the basin. The alignment of back slopes of two or more neighboring sand plains of the same level is not infrequently so pronounced that one may fairly assume that the back slopes of these deltas represent portions of the same ice-wall; and when these back slope lines, extended across the basin, connect with morainic patches on its rim, crossing the rim at points that allow an overflow-outlet at the level of the deltas under consideration, the inference of a continuous ice-dam along the line thus traced seems quite safe. If, on the other hand, in going northward one crosses rapidly a succession of deltas whose back slopes extend east and west, the inference is strong that these deltas were not formed at the same time, but successively, as the ice withdrew.

Secondly, the levels of the lobe brows of the sand plains give an accurate measure of the levels of the temporary lakes in which they were built. The lobe brow measures the water-plane for the stage during which the lobe was built. A group of deltas of just the same altitude in a single basin probably belong to a single lake, whose level remained at that height at least so long as these deltas were being formed. The possibility of there having been several neighboring lakelets at identical levels should, however, be recognized and tested by an examination of the topographic conditions and ice-border evidence. If two deltas are at different levels, they probably represent different lakes, or different stages in the same lake, — higher and lower water-planes, — unless there have been post-movements of the land, such as tilting. The question of the arrangement of sand deltas of different levels, and the light that it may shed on the history of a lake, will be considered later (p. 273).

Certain features peculiar to individual sand plains are significant in showing how the ice retreated, its rate of melting, changes in lake-level, etc. That sand plains were built very rapidly — much faster than the ice melted back — is shown, for instance, by the extremely small ratio of backset beds to topset and foreset beds, as first pointed out by Professor Davis (a, 199). Kettle-holes, so commonly marking the places where ice-blocks were enclosed, or even buried in deposits of gravel and sand, have likewise been recognized as evidence that deposition was much faster than ice-melting.

In certain cases, sand plains show a twofold level, having two sets of lobes, a higher and a lower set. These may fairly be taken to indicate a change of level of the waters while the delta was being built. The often observed fact that topset beds truncate the upper parts of foreset beds is believed by Professor Woodworth and others to indicate a change of level, giving a true erosion unconformity.

Importance of Sand Plains in Southern New England.

It may truly be said that sand plains are the most plentiful and the best-developed form of stratified glacial deposits in New England. Their abundance and relative perfection, along with their significance, make them a fitting subject for a study of late glacial history; at the same time, the relative — one might almost say complete — absence of other records of ice-front lakes in this area, such as wave-cut benches and scoured and aggraded outlet channels, makes sand plains doubly important. It is natural, then, that good work has been devoted to sand plains, and that the progress in the understanding of them has come from eastern Massachusetts.

The first clear presentation of what a sand plain is came from Davis in 1890 (a). Much detailed work is also recorded in papers by Woodworth, Gulliver, and Fuller; and more recently the correlation of sand plains, in order to make out the history of ice-front lakes, has yielded definite results to Crosby, Grabau, and Clapp. Perhaps the most concise example is Grabau's report on glacial Lake Bouvé (b), in which the history of a small ice-front lake in the southern part of the Boston Basin is rather thoroughly treated.

Discordance of Level of Sand Plains.

It is common in eastern Massachusetts to find that the sand plains in a single lake basin vary in altitude. Possibly the lakes were continually suffering changes of level by reason of temporary blocking of their outlets by icebergs or ice-dams, or perhaps as a result of great variation of supply of water from the melting ice. In that case we should expect to find deltas at all sorts of levels. Controlling conditions as irregular as the formation of ice-blockades would involve great irregularity in delta levels.

If, however, there is no such disturbing element in an ice-front lake, one can still see how the deltas in a single lake might vary in level; for if we consider again the normal lake history already outlined, we find that from the natural succession of lower and lower water-planes, as the ice retreats across the basin uncovering lower and lower outlets, there must be lower and lower sets of deltas. Sand plains, then, might mark different levels in the same lake; but in this case the variation would be perfectly systematic. Instead of a promiscuous arrangement of high and low deltas due to irregular blocking of outlets, there would be a definite grouping of deltas into sets, each set being composed of deltas of a single level or water-plane, and being succeeded by a lower set on the iceward side.

This step arrangement of deltas, in descending groups as one proceeds in the direction of ice retreat, has apparently been recognized by Grabau in his study of Lake Bouvé, and has been applied by Clapp and Crosby to the deltas of Lake Charles, Lake Nashua, and other temporary ice-front lakes of eastern Massachusetts.

The area embracing what Professor Crosby has called glacial Lake Sudbury is the field in which I have attempted to apply one or the other of these two schemes of arrangement of sand plains, — that of confusion of levels or that of horizontal steps.

Glacial Lake Sudbury.

The area occupied by the temporary glacial Lake Sudbury is a belt of lowland on the Framingham sheet (U. S. G. S.), reaching from Lake Cochituate northward to Concord. It constitutes the valley of the lower part of the Sudbury River, which at Concord joins the Assabet to form the Concord River, and as such flows north through Billerica to the Merrimac. The length of the old lake basin, from Framingham to Concord, is about eighteen miles; its average width is about four. That this basin was occupied by a temporary lake as the ice withdrew is well shown by the abundant sand plains which are scattered about in it, and which rise generally to the level of the lowest points on the rim of the basin, near by.

The approximate form and extent of the lake can best be seen on the accompanying map (Plate 5), in which the probable shore-lines are drawn along the contour which lies nearest the level of the adjacent sand deltas. Since these deltas vary nearly 70 feet in elevation, the shore-line follows different contours in different parts of the basin, as will be recognized when the map is compared with the U. S. G. S. contour map.

The country on the western side of the basin is much higher than that which forms the southern and eastern rim, being as a rule well above 200 feet in altitude. The Nashua basin, which lies west of the Assabet and Sudbury, was occupied in late glacial times by a temporary lake whose level was much higher than Lake Sudbury, and which drained eastward into it, as Professor Crosby has shown (b). The waters of Lake Sudbury, then, could not have escaped to the west; they must have reached south and east into the lower basin of the Charles River.

The divide that separates the Sudbury basin from that of the Charles has several gaps which must have been occupied either by outlets of Lake Sudbury or by arms of confluence with the contemporary Lake Charles. Near the southern end of the Sudbury basin in particular, there seems to have been, for a while at least, a confluence of the two lakes; for the present divide is itself made up of sand deltas and associated gravel deposits which appear to carry the water-plane of Lake Charles over into Lake Sudbury. This is seen on the map in the line of sand plains which extend from the big bend of the Charles near South Natick northwest through Morse's, Jenning's, Mud, and Pickerel Ponds to Cochituate. The pass at Morseville, south of Lake Cochituate, where the present divide is still lower (about 145 feet above sea-level), may also have been a point of confluence between Lake Charles and Lake Sudbury.

North of Cochituate, along the eastern rim of the basin, there are only two considerable sags or cols in the divide, — one east of Wayland, near the head of Cherry Brook, and one about a mile south of Lincoln station. Both these passes, however, are above the level of the Cochituate and Morseville passes, and so could hardly have served as outlets for Lake Sudbury unless they were originally lower, and have been subsequently raised by tilting.

Another pass occurs just outside the limits of Lake Sudbury as it is here defined, east of the point of junction of the Assabet and Sudbury (where the Concord River begins), at the head of Hobbs Brook in Lincoln. This is also a relatively high-level pass, about 160–170 feet, judging from the contours. The importance of these higher cols will be shown later.

Arrangement of Sand Plains in Adjoining Districts.

The sand plains of Lake Charles in Wellesley, Needham, and the southern part of Newton, mark a water-plane, the altitude of which is about 150–160 feet. This has been reported and discussed by Crosby and Clapp, who took their levels from the contour maps of the U. S. G. S. Boston and Framingham sheets. The recently revised map of the Boston area has made it possible to get these levels more accurately than before. A table follows which gives the altitudes in the district just mentioned, as they are shown by the newly drawn contours of the Boston map and maps of the Metropolitan Park Commission; also a few altitudes determined much more accurately by a hand-level survey, and one or two measured approximately by reference to bench-marks of the Metropolitan Water Board along the line of the Cochituate Aqueduct.

Big sand plain at Needham (Boston map, contours) . .	about	160′
Sand plains 1 mile N. W. of Needham " " . .	"	160′
Sand plain at S. end of Waban Lake (Met. W. B. b. m.)	"	150′
Sand plain just E. of Newton Up. Falls " "	"	150′
Sand plain north of Wellesley Hills sta. (B. map)	"	150′
Small sand plain cut by R. R., E. of Waban (hand-level)	"	154′
Big sand plain extending from Newton Centre through Eliot to Waban (lobes 500′ W. of Chestnut St. bridge 518)	"	148′
Sand plain near Woodward and Chestnut Sts. Waban . .		150′
Waban sand plain, E. of Newton Lower Falls (Metrop. Park. Com.)	about	150′

(Hand-level altitudes underlined.)

North of this line of plains, in general north of the Boston and Albany Circuit Railroad, there is a slight drop in the water-plane; for the well-known Newtonville plain has lobes at about 140 feet (by contours on the Boston map), and the little sand plain just northeast of Woodland station, which merges into the higher Waban plain, has lobes east of Washington Street at about the same height, as shown by the 140-foot contour. In general, however, all the plains in this part of the basin of the Charles, south of the Boston and Albany main line, are not far from 150 feet in altitude.

Near the Boston and Albany main line in Auburndale, West Newton, Newtonville, Newton, and Brighton, there is a very pronounced drop in the water-plane, marked by sand plains which lie about 80 feet lower than those just described, viz., at about 60 feet above sea-level. Most of these plains are rather obscured by settlement, e. g. those of Newtonville, Waltham, and Waverley.

There appear to be still lower plains near the Charles River, from the last-mentioned group northward, including one at Nonantum and one south of Commonwealth Avenue near Cottage Farm. The gravel plains of Cambridge and Arlington lie hardly more than 25 feet above sea-level.

This rather sudden drop from the 160–140-foot plains to those of 60 feet and under marks the change from Lake Charles into what Crosby has called Lake Shawmut (130), the smaller successor to Lake Charles, lying wholly within the Boston Basin.

North of Waltham the country east of the Sudbury basin is mostly high ground, nowhere low enough to meet the 60-foot water-plane which would be expected to mark the maximum height of temporary Lake Shawmut there. Naturally, therefore, there are no sand plains in that part of the district, between Lincoln and Lexington. The gravels farther east, in the Mystic River valley, from Arlington to Woburn, lie wholly below 60 feet.

Expectation regarding the Lake Sudbury Water-planes.

The work of Crosby, Grabau, and Clapp, on the temporary lakes of this region, pointed to the likelihood that the sand plains of the Sudbury basin would be found to be arranged according to the horizontal step scheme, i. e. either at a single altitude, marking a single water-plane, or in groups of decreasing altitude from south to north, marking successively lower and lower water-planes.

Clapp recognized from the contour map that the sand plains of both the Sudbury and the Charles basins, since they are over 150 feet, rise above the level of the Cochituate pass (145 feet), the lowest pass in the divide between the two basins; and the two lakes, Sudbury and Charles, must then have had a common level higher than the Cochituate pass, which formed a narrow arm of confluence. The line of sand plains from the Charles at Wellesley northwest to the Sudbury basin at Natick, was mentioned particularly by Clapp as representing an arm of confluence between Lake Charles and Lake Sudbury, during a stage when the water-level was about 160 feet. Clapp speaks of the deltas built in the confluent lakes in these words: —

"The plains at this stage of the confluent lakes [Sudbury, Charles, and Neponset] are by far the best developed of any stage. The broad deposits of Medfield, Millis, and Medway, as well as those in Wellesley, Needham, and West Roxbury were formed at this time. In Newton, they are developed as far north as the Boston and Albany Railroad; . . . West of Needham and Sherborn the plains extend through Wellesley, Natick, and Framingham, across the Cochituate water-parting to the valley of the Sudbury, where an extensive series of the same general elevation is found, extending even down the valley of the Concord River into Bedford and Billerica" (a, 265).

According to this, Clapp recognized the 160-foot level as one that was maintained very long in Lake Sudbury; or, to use his words again: —

"While on the west the ice had retreated as far north as Billerica, it still occupied Boston Bay and a large part of the Boston Basin" (a, 265). (See also Crosby and Grabau, 129).

If his view is correct, the ice-front, just before Lake Charles dropped down to Lake Shawmut, must have extended from near Riverside due north for about fifteen miles to Billerica. Although this extreme irregularity in ice-front is not impossible, one might rather expect that the ice would have melted back from eastern Massachusetts with its front more nearly east and west. In other words, one would naturally look for evidence that at the time the last 160-foot sand plains were formed in Lake Charles in Newton, the ice-front to the west stood somewhere in the Sudbury valley between Framingham and Concord; and that when further melting let Lake Charles down from 160 feet to the 60-foot level of Lake Shawmut, the level of Lake Sudbury fell from 160 feet to the level of the lowest pass on its rim, — the Morseville pass, at about 145 feet. In this case, the sand plains of the Sudbury valley would not mark a single water-plane, but two water-planes, the first at 160 feet the confluent stage, in the southern part of Lake Sudbury, and the second at 145 feet, the stage when Lake Sudbury was tributary to the lower Lake Shawmut by way of the Morseville pass.

From the preceding paragraphs it appears that the levels of sand plains in Lake Sudbury, according to the simple scheme of horizontal steps which Grabau used for Lake Bouvé, Crosby for Lake Nashua, and Clapp for Lake Charles, would show these features: —

(*a*) No sand plains could occur above 160 feet.

(*b*) Either the plains between Framingham and Concord would all mark a level of about 160 feet, or the plains in the southern part would be 160 feet and those in the northern part 145 feet, with possibly double-lobed plains in the zone of change from the higher to the lower level. Concerning the use of the various passes through the divide, as outlets of Lake Sudbury, this would be true: —

(*c*) The Cherry Brook and South Lincoln passes, being above 160 feet (as well as above the more southerly Morseville pass), could never have served as outlets for Lake Sudbury.

(*d*) The Morseville pass alone could have acted as a spill-way, and that only in case Lake Charles fell to Lake Shawmut while the ice-front lay somewhere between Framingham and Concord.

The Horizontal Step Scheme applied to Lake Sudbury.

The four points in the last paragraph may be considered in order:

(*a*) First, regarding the maximum height of the sand plains. According to the contours of the Framingham sheet, some of the sand plains of the Sudbury valley are above 160 feet. The splendid large delta at North Sudbury, for example, is bordered by a 180-foot contour; the large plain east of Maynard, occupied by the American Powder Company, is shown by a 200-foot contour; and the plains in Concord near Lake Walden and east of the village rise apparently to at least 180 feet. Careful levelling not only confirms the idea that these plains are well above 160 feet, but shows that many other plains which from the map might be taken as 160 feet in elevation are really 10, 15, or 20 feet above that level. A glance at the map (Plate 5) will show this.

(*b*) The sand plains of Lake Sudbury do not fall even approximately into horizontal water-planes at 160 or 145 feet. The contours, of the U. S. G. S. map, poor as they are, express rather clearly the strong discordance of levels. Taking the contours as truthful only within 20 feet, one finds that the plains do not agree in altitude. One at Wayland, for instance, is bordered by a 140-foot contour, while that at Maynard, about eight miles further north, rises to 200 feet. The real test of accordance, however, comes when careful levelling is done to determine accurately the levels of lobe brows of the sand plains. The figures on the map (Plate 5) show the great range of altitudes that accurate levelling brings to light. Out of sixteen different sets of lobes, measured in this way, only four measure within five feet of 160 feet, and they run all the way from 137 to 201 feet.

(*c*) Several things point to the probability that the Cherry Brook pass once drained Lake Sudbury. Just west of it in the valley, near Wayland, the level of the sand plains suddenly drops from about 190 feet to about 165 feet, the approximate level of the pass. Along the courses of brooks that head in the pass, as one follows them down-stream, are suggestions of former occupancy by more powerful streams, in the from of boulder-paved stretches, aggraded floors, and pot-holes. The detail of this evidence will be given later. While not at all strong, it is at least suggestive, when taken in connection with the better evidence of water-planes above the level of 160 feet.

(*d*) The Morseville pass near Steep Rock, and the course of the brook from that point southeast through Little's Pond to the Charles River, show no sign of scouring. The evidences of outlets are in general so poor in this region, however, that their absence here is of little weight in settling the problem.

The horizontal step scheme, therefore, does not find confirmation in the water-plane evidence in the Sudbury valley. Although this scheme has been thought to explain the grouping of deltas in the adjoining lake basins, it is distinctly the wrong explanation in the case of Lake Sudbury.

Other Possible Explanations.

Whatever theory is true for the grouping of the Lake Sudbury deltas must account for these facts: —

(*a*) The great range of level of the deltas.

(*b*) The large number of high-level deltas, 40–60 feet above the level of the Morseville pass, and 20–40 feet above Clapp's 160-foot "confluent" water-plane.

(*c*) The probable use of Cherry Brook pass as an outlet, although it stands fully twenty feet higher than the Morseville pass at the first-opened end of the basin.

These requirements seem to be met by two[1] theories, — that of irregular fluctuation of lake-level by reason of ice-dams, as already mentioned on page 273, and postglacial tilting of the land in such a way as to throw the levels of an originally horizontal step-system into confusion. Early in the field season my problem was resolved into this, — the collection of data by which I might choose between the two theories, ice-damming or postglacial tilting.

The Ice-Dam Theory.

The condition of delta levels which might be expected as a result of ice-dams or icebergs stranded in the outlets of glacial lakes has already been mentioned. Because blockades might happen at any time, not at regular intervals, the grouping of high and low deltas would be haphazard rather than systematic. By great ice-dams at the outlets the water-level could possibly be raised at times 40–60 feet above the lowest notch in the rim of the basin, so that deltas would be built at that height and higher cols might perform the duty of the one temporarily blocked by ice. One thing should be noted: although lobes might be built high above the level of the lowest col, at a time when the outlet was temporarily blocked by ice and the lake-level raised, never could lobes be built at a level below the level of the col, for the lake-level could not sink lower than that. This point is useful as a test between the ice-dam and tilting hypotheses; for by tilting extraordinarily low lobes may be produced. Haphazard grouping of levels, then, and the absence of lobes lower than the level of the lowest col, are what we should expect from the ice-dam hypothesis.

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[1] A third possible explanation has been proposed by Dr. Clapp in a recent paper on Lake Charles, — viz. a condition of extreme irregularity in the melting ice, involving a network of little lakelets at somewhat discordant levels. This will be considered in a later paragraph.

Tilting in New England presumable from Other Evidence.

Everywhere that glaciated regions have been studied in detail there is evidence of postglacial tilting. DeGeer's work on the raised shore-lines of Scandinavia prove that there, at least, the profound postglacial movements were confined almost perfectly to the area that had been covered by the ice-sheet, as if the earth's crust had sunk beneath the weight of the ice, to rise again when it withdrew (a, 66; b, 25).

In Lake Agassiz, the present slanting attitude of the old shore-lines is believed by Upham to be almost entirely the result of a rise of the land when the ice left it. These tilted shore-lines are exhaustively described and the cause of tilting thoroughly discussed in the monograph on Lake Agassiz (Upham, d). The rate of tilting is usually only about a foot per mile, but towards the northern part of the region it becomes nearly three feet per mile (d, 426, 474–486).

In the Great Lakes region, Taylor has traced the tilted water-planes of the lakes of late glacial times, and has worked out the rate of tilting. In the case of Lake Nipissing, this tilt rate is found to be only about seven inches to the mile; but in other cases it is much higher. The tilting measures most in a direction north 25° east (c, 652).

The work of Gilbert and Spencer on the shore-lines of Lake Iroquois and Lake Warren, the large temporary lakes in the region of Lake Ontario, show that the withdrawal of the ice from that district was accompanied by a very considerable rise of the land, by which the horizontal beaches were tilted into a slanting position. About Lake Ontario the shore-lines of extinct Lake Iroquois are tilted at an average rate of three and a half feet to the mile (Gilbert, 603). In the vicinity of Cape Rutland, north of Syracuse, the rate is about five feet to the mile (Spencer, 128).

In western New York, Fairchild finds that the direction of greatest tilt is between north 17° east and north 20° east (e), indicating "that the isobases of the greater area are curving lines with convexity southward." In central New York, since the Iroquois beaches in a direction less than three degrees south of east show a tilt rate of only 0.66 feet per mile, the direction of maximum tilt is apparently almost north and south. This suggests that the curve of the isobases continues eastward across New York State, and makes it seem probable that in New England the tilt would be greatest in a direction nearly due north and south, — surely only a few degrees east of north, and quite likely a few degrees west of north.

DeGeer's summary of the evidence of postglacial tilting in New England, in the form of raised marine beaches, benches, and sea-floor sediments between Massachusetts and the Provinces, is the most comprehensive and reliable study yet published. Incomplete as the evidence is, one cannot deny that there has been a postglacial uplift of the north with respect to the south. The discovery of further details, like that by Tarr and Woodworth of the beaches at Cape Ann (Tarr), will doubtless some day furnish the data for determining with more accuracy the true rate of tilt along the coast and the direction of the greatest slant. In the mean time, can we not gather valuable evidence of tilting by studying the water-planes of temporary ice-front lakes like the Sudbury, Nashua, and Charles?

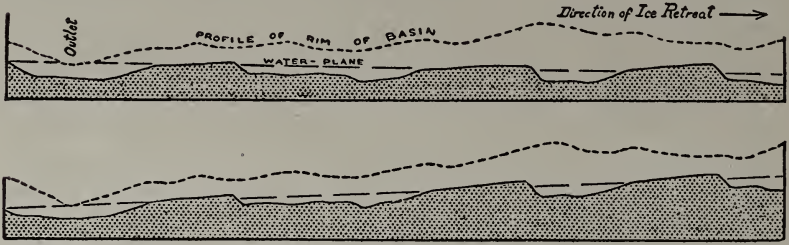

FIGURE 3.

Diagrams showing how postglacial tilting produces a discordance of altitudes among sand deltas.

In the upper figure, three deltas stand at the same altitude, marking a horizontal water-plane which is controlled by the height of an outlet at the further end of the lake. In the lower figure this region has been tilted, so that the three deltas stand at different altitudes, marking a slanting water-plane. The deltas now stand higher than the outlet col.

To sum up: From the work of Taylor, Gilbert, Fairchild, and DeGeer, we might reasonably expect that whatever evidence came to light would show a tilt towards the south of a few feet to the mile, with its greatest slant in a direction about due north and south (considerably west of the N. 17° E. line of central New York).

The Probable Effects of Tilting on Temporary Lake Features.

Taking the typical temporary lake, with its successively lower outlets and sand plains in the direction of ice-retreat, let us see how tilting will rearrange the levels.

To take the simplest case, — suppose that a single water-plane, marked originally by a set of sand deltas with brows at a common level and an outlet at a level slightly below them, is tilted evenly, with a relative elevation of the iceward side (see Fig. 3). After this movement, just as before, all the brows of the sand deltas lie in a single water-plane; but the plane is no longer horizontal, — it slants away from the ice. The sand deltas nearest the ice-field have been lifted higher than those farthest from it, the brows of the two deltas at these two extremities of the lake measuring the greatest difference of elevation of the inclined water-plane, and the deltas intermediate in position showing intermediate elevations of a measure proportionate to their distances from the two extremities. The outlet associated with these deltas, originally at or somewhat below the horizontal water-plane, will of course now be found at or a little below the slanting water-plane, as shown in Figure 3. If its position is at the further extremity of the lake (relative to the ice), or if it is at the further end of the water-plane for its stage, its level will be the lowest point marked on the water-plane; but in case the outlet was on the side of the lake, and icewards from the first delta built at that water-plane (a condition of things made possible by an irregular ice-front), its actual altitude measured after tilting will be higher than that of the sand delta whose level it once controlled (see Fig. 4).

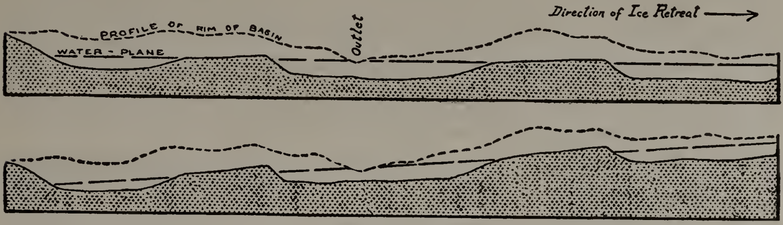

FIGURE 4.

Diagram showing how postglacial tilting, under certain conditions, may place a delta below the level of the corresponding outlet col. In the upper diagram, the ice-sheet has melted back more rapidly along the rim of the basin than in the basin itself; consequently the first delta built — the one on the left — belongs to an outlet col on the iceward side. With further retreat, a second delta has been built, on the right. In the lower diagram, the region has been tilted; and the first-formed delta has thus been brought below the level of the outlet.

Since in the lakes of eastern Massachusetts there is not usually a single water-plane, but several, it is worth while to consider how a set of these will look when tilted. In their original position, as we have seen, the deltas occur in groups, each group marking a horizontal water-plane, and standing higher than the group that lies icewards from it. Between the brow of any sand delta of the higher group and that of any delta of the lower group, there is a difference of elevation equal to the difference of the lake-level in the two stages. The outlet for each water-plane has its position just below the lobe-brow levels, and is likely to occur at or near the outer extremity of the water-plane. Now, if the region be tilted, each water-plane is tilted as already discussed, and the brows of the plains in each group will therefore indicate a rising of the water-plane icewards. The original drop from one water-plane to the next can no longer be measured by the difference in altitude between the lobe brows of any two representative deltas, for the original difference of elevation between them has been modified by the tilt. It may be that some of the deltas of the earlier, higher water-plane now stand actually lower than some of the deltas of the later, lower water-plane. The sand deltas, then, after tilting, should ascend icewards, but with a drop in elevation at each new water-plane. The relation of the altitudes of outlets would likewise be disturbed. Take, for example, any two adjacent outlets controlling the water-planes of two neighboring groups. Before tilting, the iceward outlet is the lower. The effect of tilting is to raise the lower outlet toward, to, or even above the level of its neighbor. The relative altitude of the two after tilting will depend on (*a*), the original difference of altitude (*b*), the distance apart of the outlets, measured in the direction of the tilt, and (*c*), the rate of tilting.

If the tilting of the extinct lakes was a simple uniform one, taking place after all the deltas had been built, the tilted water-planes should of course all have the same slant; in other words, the water-planes should in that case be parallel. But if the tilting was already going on during the retreat of the ice and the building of the deltas, the older water-planes at the further end of the lake would have been tilted more than the younger water-planes. Diagrammatically, the two cases would appear like Figure 5. Gilbert speaks of the application of this principle to the lakes of the Ontario basin (603).

In summing up the condition of lobe brow and outlet levels for a lake which has gone through the normal ice-front history, plus postglacial tilting, this may be said: the sand plains should be resolvable into groups, each group being composed of deltas whose lobe brows fall into a single tilted water-plane. In each group one should find, as he proceeds icewards, a steady increase of altitude of the brows, until he reaches a new water-plane in the vicinity of a lower outlet, where a sudden drop of altitude to the lower water-plane would be followed by a new group of ascending deltas. Such an arrangement may conveniently be called a slanting step-system.

Methods and Results of Levelling in Lake Sudbury.

To determine whether the Lake Sudbury deltas lie in a slanting step-system or only in haphazard fashion, a good deal of detailed levelling was necessary. Through the kindness of the Division Engineers of the various railroads and of the Engineers of the Metropolitan Water Board, I secured bench-marks which in almost every case I could conveniently use as a base, — such as the top of the rail at a certain bridge, road-crossing, or turnout, or the capstone of a culvert along an aqueduct line. From such a starting-point, with a rodman, I ran levels over a circuit as short as possible, ranging from a few hundred feet to three miles, using in some cases a surveyor's spirit-level, but more often a Locke hand-level, which proved to be a much more rapid means of levelling, and nearly as accurate. The probable error by this method was not over one or two feet per mile. On the map (Plate 5) all of these accurately determined levels and the lobe brows from which the average height has been computed are shown in black figures, while other altitudes determined by aneroid or rough computation are shown in parenthesis. These last-mentioned levels involve an error of from 5 to 20 feet. All altitudes are referred to mean low water, Boston City base.

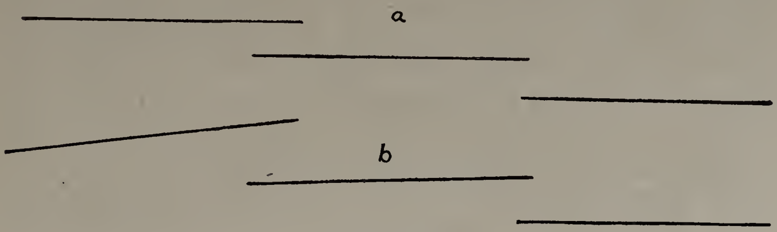

FIGURE 5.

Effect of tilting a step-system of three horizontal water-planes, (*a*) after the ice has withdrawn from the region, or (*b*) while the ice is retreating across the region. In the latter case, the water-plane which is first abandoned is tilted more steeply than its successors.

A study of the map will bring out the following facts as to the general arrangement of deltas.

In the southern part of the basin, about Lake Cochituate, the sand plains lie at about 170–180 feet, i. e., the highest lobes mark a water-plane at that altitude; but in more than one case there are lobes at different altitudes on a single sand plain, as if marking changes of level during the construction of the delta. This is remarkably true of the big sand plain just east of Saxonville, which has at least four different sets of lobes.

The two sand plains north of the last, which are cut by the Sudbury Aqueduct, and the plains northwest of them in Sudbury, are higher, — about 190 feet — although these also have one or two lower sets of lobes.

Going on towards Wayland, one finds there a sudden drop in altitude of the sand plains down to about 160 feet, represented by the three plains near Wayland station. The plain cut by the Massachusetts Central Railroad west of the Sudbury River stands at an intermediate height, however, 175 feet.

From Wayland northward through Lincoln to Concord there is a steady increase in height of the sand plains, — 160 feet at Wayland, 175 feet at South Lincoln, and 195 feet at Lake Walden. Across the river on the west side of the valley, the plains show the same sort of an increase in height going north, through 175 feet near Sudbury Centre to nearly 200 feet around North Sudbury, Maynard, and Concord Junction. Right at the north end of the Sudbury basin, where the Concord valley begins, there is a second pronounced drop in level of the sand plains from 200 feet to about 150 feet. The high plateau east of Concord village is the farthest north of the 200 feet group of deltas. Beyond that, the gravels occur only at lower levels.

In general, then, the discordance is not haphazard, as it would be if it depended on the ice-blockade theory. It is quite systematic; the plains rise from Cochituate north to Wayland, drop down there from about 190 to 160 feet, then rise steadily from 160 to 200 feet at Concord, where there is a second drop. There is a strong suggestion, in short, of a slanting step-system.

Water-Planes slanting southward, Seven Feet per Mile.

The first three sand plains to be measured with a hand-level were the Lake Walden plain (194 feet) and the two deltas east of Wayland, — one south of the railroad (161 feet), and one north (163 feet). The two deltas at South Lincoln, halfway between the Wayland plain and the Walden plain, had been found by aneroid readings to be of intermediate altitude, somewhere between 170 and 190 feet. Plotting the three accurately measured plains in cross-section, I found that they fell into a single straight line. Then, on the assumption that all the plains between Wayland and Concord had originally stood in the same horizontal plane, and that this plane had since been tilted up on the north, I plotted the position of the two South Lincoln plains, and found that in order to lie on this tilted water-plane the southern one should have lobes at 177 feet and the northern one at 180 feet. Hand-level surveys, made a few days later, fulfilled the prediction; for four lobes measured on the south plain averaged 179 feet, and three on the north plain stood at about 182 feet. Inasmuch as the circuit for this levelling, from Lincoln station to the plains and back, was a very long one — three miles — involving a probable error of three feet, the results in this case were fully as satisfactory as could have been expected. The water-plane thus determined slants southward at the rate of about seven feet per mile.

Having thus gained faith in the tilting hypothesis from the element of fulfilled prediction in levelling, I continued to collect data, and found that in nearly every case the measurements of lobes fell on slanting water-planes which passed through one or the other of the passes in the rim of the basin. The final result of this grouping of deltas is shown in Plate 4, where all of the measured lobes are plotted to scale along a north-south line, and the slanting water-planes drawn through them. It will be seen that the Cherry Brook water-plane is determined by lobes measured on nine separate deltas. Between Wayland and Concord Junction all the deltas measured, except two, lie close to this single water-plane, as does also the Cherry Brook pass itself. The other water-planes are not so well determined; but they explain all the features save a few which will be discussed later.

On the basis of the Cherry Brook plane, then, there seem to be five parallel water-planes marked by the lobes of deltas in Lake Sudbury: —

(*a*) The water-plane of confluence between Lakes Charles and Sudbury, ranging from 150 to 191 feet (sand plain at Waban Lake to two plains cut by the Sudbury Aqueduct south of Wayland). (*b*) The Morseville water-plane, marking the stage when Lake Sudbury drained down into Lake Shawmut through the Morseville pass. This stage is shown by lobes of the plains about Saxonville and Wayland. (*c*) The Weston water-plane, marking a stage of short duration, brought about by the uncovering of part of the Cherry Brook pass before the lowest part of the pass was free of ice. The lobes that seem to mark this range from 164 to 175 feet. (*d*) The Cherry Brook water-plane, which is marked by nearly all the deltas between Wayland and Concord, ranging from 160 to 200 feet. (*e*) The Hobbs Brook water-plane, marked by the lower deltas of Concord, with lobes in the vicinity of 150 feet.

Recognizing that a grouping into seven-feet-per-mile water-planes may be incorrect, for reasons which will be brought out later, let us nevertheless trace the probable history of Lake Sudbury on the basis of a postglacial tilt of seven feet per mile towards the south. For this purpose the groups of the system of slanting steps may be considered in order of their age.

Probable History of Lake Sudbury.

THE STAGE OF CONFLUENCE. — The stage of confluent lakes which saw the birth of Lake Sudbury seems to be marked by deltas which occupy the southern part of the Sudbury basin as far north as the Sudbury Aqueduct south of Wayland. They apparently form a continuous belt from the Charles River, near Lake Waban, northwest across the divide to the Sudbury basin at Cochituate village. They also occur on the divide just south of Natick. Their distribution in the two basins in such a way as to actually form the present water-parting at Natick and Cochituate, together with the fact that the deltas are considerably higher than the Morseville pass, point to a state of confluence between the two lakes while the ice in the Charles valley was retreating towards the present position of the Boston and Albany Railroad and its front in the Sudbury valley was receding towards Wayland.

The levels of most of the plains of this stage have been determined only approximately. It has been hard to secure convenient bench-marks from which to measure some of them; consequently aneroid readings and map contours have been relied on for levels. Moreover, the plains in the southwestern corner of the basin, around South Framingham and southwest of Lake Cochituate, have not been mapped.

THE MORSEVILLE STAGE. — The drop from Lake Charles to Lake Shawmut, when the ice had withdrawn to the position of the Boston and Albany Railroad, must have caused a simultaneous drop in Lake Sudbury from the confluent level down to the level of the Morseville pass. The lowering of level seems to have come when the ice-front in the Sudbury basin was near Wayland, and while the deltas at the Sudbury Aqueduct were being built; for these have lobes at two levels which apparently fall into a water-plane with the Morseville pass and with a set of lobes on the Saxonville delta west of Lake Cochituate.

The Saxonville plain deserves special mention, for it has lobes at several distinctly different levels. On the northwest side, where these lobes are best seen, the plain has clearly been built outward towards the northwest from an ice-front at the northern end of Lake Cochituate. The occurrence of lobes in increasingly lower and lower sets on this single plain indicates that the water-level fell while the delta was being built, possibly in successive stages. The way these lobes fall on the probable water-planes of Lake Sudbury is seen in Plate **4**. Those of the highest set, at about 185 feet, are irregular, and have been measured only approximately. They seem to represent the stage of confluence. Below them, at the northwest corner of the plain, are two or three well-formed lobes, at 161–165 feet, which have a peculiar and very striking surface of cobblestones, as if all the finer sand had been washed down from them after the water-level fell. These lobes seem to fall on the Weston water-plane (the next one to be considered). Between two of them a lower lobe (at 149 feet) has been built; and this falls on the Cherry Brook water-plane. Lowest of all is a terrace with several fine lobes, at 137 feet, which have a remarkably sandy composition. On the south side of the plain, southeast of Saxonville, lobes occur at 167–172 feet, and a lower set at 152 feet. The 167-foot level, marked by at least two lobes, falls on the Morseville water-plane. The 172-foot lobe probably represents the time when the waters were just falling to the level of the Morseville pass, or when the pass was first occupied by an outlet which cut down five feet before the 167-foot lobes were formed. In all cases, the higher lobes lead down to the lower lobes by smooth slopes. It seems probable, when these lobes are identified with the various water-planes, that the Saxonville sand plain was being built forward from a large ice-block in Lake Cochituate when the main part of the ice had retreated northward beyond Wayland, and perhaps even as far as Concord.

THE WESTON STAGE. — While Lake Sudbury stood at a level controlled by the Morseville pass, the ice-front receded from the Aqueduct plains towards the present position of the Massachusetts Central Railroad. On reaching this position it must have uncovered the pass in the Sudbury-Charles divide that is occupied by the railroad. Although this pass now stands higher than the Morseville pass (over 160 feet, whereas the Morseville pass is 145 feet), its greater height seems to be due to postglacial tilting, judging from the slant of the water-planes as marked by the lobes of deltas. As already mentioned, also, there is a pronounced drop in altitude of deltas just west of the pass in Wayland, from 190 feet to about 160 feet, the general altitude of the pass.

Before the lowest part of the pass (north of the railroad, near the head of Cherry Brook) was opened, there was of course in all probability a partial evacuation of it, along the northern slope of the high ground south of Weston village. The well-formed sand plain cut by the railroad just east of East Sudbury station has lobes at 175 feet which may very likely have been built at this time. There are lobes also on both the north and south sides of the Saxonville delta, which fall into a tilted water-plane with this 175-foot delta. That there are so few deltas marking this stage is natural enough, because it is essentially a temporary stage which was soon followed by renewed lowering of water-level as the ice withdrew so as to allow the water to pass eastward by lower paths, — first by the little forked brook half a mile northwest of Weston station, and later by Cherry Brook. These two probable lines of escape are so nearly at a common level that there has been no attempt made to differentiate two water-planes for them.

THE CHERRY BROOK STAGE. — The deltas built while the Cherry Brook pass was a spill-way mark by far the best-determined water-plane. Lake Sudbury seems to have been maintained at this height from the time the Wayland deltas were formed until the ice-front had withdrawn eight miles to Concord; for between Wayland and Concord the lobe altitudes of nearly all the deltas lie on a single slanting water-plane. The cross-section (Plate 4) shows how closely eight of these deltas fall on the water-plane. It is also remarkable that if the water-plane be extended south from Wayland it just hits the 149-foot lobe of the Saxonville delta. This seems to show that the Saxonville delta was still being built out from the Lake Cochituate ice-block when the Cherry Brook pass was opened.

The two large plains in North Sudbury seem to be the only deltas in the northern part of the basin whose lobes do not lie on the tilted Cherry Brook water-plane. Since there is no reason to doubt the accuracy of measurement of their altitudes, they are thus far unexplained. The splendid big delta west of the railroad has lobes at 201 feet (14 to 20 feet too high for the water-plane); the delta east of the railroad has lobes at 193 feet (6 feet too high).

THE HOBBS BROOK STAGE. — It is possible that the pass at South Lincoln became an outlet to Lake Sudbury when the ice had retreated that far; but there is no evidence of it in slightly lower lobes or in signs of scouring along the courses of the brooks that head in the pass. The height of the pass, moreover, is very nearly as great as the computed height of the Cherry Brook water-plane. Consequently it seems reasonable to suppose that not until the ice had melted back beyond Lake Walden, so as to uncover a pass at the head of Hobbs Brook, three miles to the east of Concord, did Lake Sudbury suffer a marked lowering of level. With the opening of the Hobbs Brook pass, the water seems to have fallen about 50 feet, judging by the height of the lower deltas at Concord and Concord Junction. Since this new water-plane, 50 feet below the other, begins where the Concord River begins, it would perhaps be appropriate to consider the opening of the Hobbs Brook pass as marking the death of Lake Sudbury and the birth of a new lake, Lake Concord. That the transition was not immediate is shown by lobes of intermediate altitudes on the sand plains near Concord Junction.

Outlets of Lake Sudbury.

In several papers on the temporary glacial lakes of central New York, Fairchild describes a large number of well-developed outlet channels. Next to delta deposits, these channels are the clearest records of the extinct lakes of this region; and they are certainly the most striking of all. They are described as often heading in low marshy ground on a water-parting, called a "swamp col" by Fairchild (e, 36, 37, 38, 58, 61). As channels with definite walls, they run often nearly straight for a mile or so. One which drained Naples Lake, given as a good example of an abandoned river-bed, is described as "over a mile long, 20 to 25 rods wide, with banks 15 to 25 feet high, and a flood plain of varying width," and a "pavement of cobbles and boulders in the bottom of the channel," which "is still well shown through the vegetal accumulation" (a, 362). When, as in this case, the channel is cut in drift, the banks and flood plain seem to be well developed. Not infrequently, however, a channel has rock walls and a swampy bottom. Some of the old outlets of Genesee Lake are rock gorges with swamps partly occupying the channel floors (c, 434, 435, 436, 437, 438). In certain cases, deltas built into these channels from side ravines have levels of from 70 to 80 feet above the channel floor, seeming to indicate a down-cutting of the floor 60 to 70 feet since the channel first opened (c, 435). Other outlets of Genesee Lake are broad, with flood plains. At the lower ends of these channels are commonly plains or deltas of detritus, built out by the stream which cut the channel above (e, 38, 52, 54). One at Cedarville is more than a square mile in area. Most striking of all are the deep rock gorges at Syracuse, which mark outlets of glacial Lake Warren. One of these is two miles long, 8,000 to 10,000 feet wide at the bottom, and 125 to 150 feet deep, with nearly vertical walls; another is a limestone gorge, with a cataract cliff 160 feet high, at the foot of which is a deeply excavated pool (e, 60).

In New England, the outlets of temporary lakes are not nearly so well defined. In the case of Lake Nashua, Crosby has discovered what he considers to be evidence of outlet scouring in the pass at Clinton, — a sag in the divide, which must have been used as a spill-way, judging from the height of sand plains in the Nashua valley near by. Professor Crosby says: "This is an ideal outlet — narrow, well-defined, and with every indication of a strong stream flowing swiftly down around Snake Hill into the valley of North Brook. In the lower part of its course, especially, this stream washed away all the fine parts of the till, and its path is now strewn with thousands of residuary boulders. That this is the work of a long-continued torrent, and not of some transitory cloud-burst, is proved by the pot-holes to be seen in the bed at North Brook at West Berlin, in situations which make it well-nigh impossible that they can have been formed by the modern brook" (a, 318).

Similar traces of spill-ways are to be seen in some of the cols in the eastern rim of Lake Sudbury, and along the courses of the brooks that head in them. A half-mile northwest of Weston station, the contours show a forked pass at about 160 feet, occupied by the headwaters of a brook and crossed by a road that runs north from the village. According to the contours, this col is the lowest northeast of the Saxonville pass, being probably 10 feet lower than the one south of Weston village. It is therefore a place which deserves critical examination for evidence of outlet scouring.

Going north along the road from the railroad west of Weston station, one crosses the western end of a ridge of bed rock with a thin till covering. Reaching the southern fork of the brook, one finds west of the road a broad swampy area, well wooded and almost flat, at an elevation of 163 feet (aneroid). Beginning directly at the road and extending east along the line of the brook, is a pavement of boulders so thick as to be remarkable even to one not looking for features of the sort. The paved zone is about 100 feet wide, and consists of boulders of moderate size, as well as a few cobbles. It follows the lowest ground along the brook, which is about 3 feet wide. About 300 feet east of the road, the pavement rather suddenly stops, and the course of the brook is through a narrow grassy flat, which soon broadens out into a broad swamp at the junction of the two headwater forks. The absence of boulders and blocks along the brook just up-stream may be largely or wholly due to the construction of a private road across the brook about 300 feet east of the highway, — the rocks having been collected for its construction. Where the northern of these two brooklets crosses the road, one finds on the west side of the road, going up-stream, a few bare ledges and many blocks, including some large boulders, and beyond these the flat swampy ground already mentioned as the source of the brooklets. The elevation at the road at this point is 165 feet (aneroid). Going down-stream from the road, one finds a pretty continuous boulder pavement as far as the broad meadow at the junction of the two brooklets, though the boulders are much thicker in some places than in others. There are a few bare ledges here, also.

On both these brooklets the boulder pavement is a distinct and striking feature. There is no such abundance of blocks on the slopes which lead away from the brooks to the north and south. The distribution is emphatically along the two lines of lowest ground; and the width of the pavement together with the general good size of the boulders seems to indicate that scouring much stronger than that of the present little stream has gone on in the past, washing the finer parts of the thin till cover down-stream, and leaving bare ledges and a thick pavement of boulders. There are no steep banks, however, enclosing the paved zone, such as one might expect to find.

Down-stream from the junction, the brook follows generally a rather broad flat meadow; and though boulders may once have been plentiful at certain points along its course, there is no longer anything like the boulder pavement seen up-stream. From the railroad for about 500 feet southward along the brook, however, there are a good many boulders, possibly of some significance. Below this the valley becomes extremely broad, flat, and swampy. These flat meadows along the brook are evidently aggraded parts of its valley; and they may have been built up by the supply of gravels and fine material from the scoured boulder-paved pass up-stream.

Along the course of Stony Brook, in several places, particularly between Kendal Green and Roberts, there are stretches of boulder pavement similar to those just described. Doubtless the brook gets its name from this fact. Moreover, the two large pot-holes beside the railroad embankment, near the northern end of Stony Brook Reservoir, may have been formed by the action of a powerful stream that was the outlet for Lake Sudbury. Whatever water spilled over at Weston, down Cherry Brook, at South Lincoln, or at the head of Hobbs Brook, would have run into Stony Brook; and marks of scouring, such as boulder pavements and pot-holes, should be expected wherever the course of the stream was down a steep slope.

Heading on the southeast side of the Hobbs Brook pass, Hobbs Brook flows south into Stony Brook, a large part of its course having been dammed up to form the Cambridge Reservoir. On the northwest side of this reservoir, about a mile north of Prospectville, near where the parkway joins Concord Avenue, is a small exposure of bare rock, rounded and hummocky, as if worn by a powerful stream. About a quarter of a mile below the reservoir, along the course of the brook, is a pavement of boulders about 100 feet wide and 300 feet long, — again suggesting the former occupancy of the course of Hobbs Brook by a powerful stream at a time when the pass above it served as a spill-way.

Similar evidences might be expected below the Morseville pass, in the brook that drains Little's Pond, but I have looked in vain for them. The brook that heads in Weston village shows no sign of scouring. Just where its course begins to be steep, a millpond has been formed, and the aspect of the ground is otherwise changed by artificial grading. Cherry Brook exhibits no boulder pavement.

Direction and Rate of Tilt is questionable.

Judging from the fact that 8 of the 11 accurately levelled deltas between Wayland and Concord fall nearly in line for a single water-plane when plotted with respect to a north-south line, as in Plate 4, and that they do not harmonize so closely when plotted with respect to any other direction, it seems safe to say that the direction of maximum tilt is somewhere about due north and south. The rate of tilt measured along this slanting water-plane of the Cherry Brook stage is a little over 7 feet per mile, steeper than what might be expected from the evidence of Gilbert, Fairchild, and DeGeer. The other water-planes all lie parallel to this well-defined Cherry Brook plane, — that is to say, the same tilt is recorded by all.

Over against the striking conformity of delta levels to the 7-feet-per-mile water-planes, there are a few details which suggest that the tilt is even steeper and the grouping consequently somewhat different from that just given.

Two fairly well developed deltas at North Sudbury which should fall on the Cherry Brook water-plane if the other deltas are correctly grouped, stand 6 and 14 feet too high, respectively. These were carefully levelled, and there is no reason to doubt their altitudes, 193 feet and 201 feet. Ice-damming might account for this, or it is possible that the deltas were built in a little high-level lakelet held in by an irregular ice-front against the western side of the valley, but there is nothing to support these explanations save the necessity for them. Tilting could explain the extraordinary height just as well, — but not tilting at the rate of 7 feet per mile.

The extraordinarily low lobes on the northern side of the big Saxonville delta, at 137 feet, have already been spoken of; but their altitude has not yet been explained. These five or six lobes are unusually well formed, and compel attention. On seeing them, my first idea was that they belonged to the Cherry Brook water-plane; but that plane, if extended southward from Wayland with the 7-feet-per-mile slant, hits the Saxonville delta at 149 feet, where there is one lobe, to be sure, but only one, and to all appearances a lobe that registers simply the transition from one long-lived water-plane, here 163 feet, to another permanent water-plane at 137 feet.

Curiously enough, the "too low" lobes of Saxonville and the "too high" 201-foot delta of North Sudbury can be brought by plotting into a single slanting water-plane which passes through the two Wayland deltas and just above the Cherry Brook pass, as shown in Plate **3**. The Cherry Brook water-plane thus drawn has a slant of over 11 feet per mile. The deltas in Lincoln and Concord falling below this steeply inclined water-plane might perhaps owe their level to an outlet through the South Lincoln pass.

Drawing other 11-foot-per-mile planes for the higher Saxonville lobes, one gets some curious surprises in the way in which lobes fall on single water-planes; but the difficulties in explaining the occurrence of these water-planes are so great, and the slant of them is so extraordinarily steep, that little faith can be placed in them.

Plotting the delta levels with respect to an axis in any other direction seems to bring no better results. Further detailed work is needed, if they are all to be brought into perfect harmony with a single slanting step-system.

While the 137-foot lobes are so troublesome, in being too low for their water-plane, they have a peculiar value. Their altitude is a little below that of the very lowest col in the divide, — the Morseville pass, — which, judging from data secured from the Metropolitan Water Board, must be over 140 feet. As mentioned on page 281, this condition of things seems to be explainable only by tilting.

The Theory of Many Lakelets.

In a recent paper on the sand plains of glacial Lake Charles, Clapp states his belief that the ice melted off from eastern Massachusetts in an extremely irregular fashion, so as to form a network of marginal lakelets, in which, here and there, the deltas were built. This theory seems to account for the prevalent discordance of altitude in neighboring deltas; and it is based on observations which Clapp sums up under four heads (c, 207). In reviewing these features in order, let us consider whether they are to be seen in Lake Sudbury or not.

(1) The plains in the northern part of Lake Charles, according to Clapp, are distinctly marginal in their position, — grouped about the shores and islands of the extinct lake, as if they had been built not in an open water body but in single lakelets which formed along the sides of the basins while the ice still occupied the central portions. This marginal distribution of sand plains is not distinctly the rule in Lake Sudbury. Most of the large deltas are not far from the rim of the basin; but since there was shallower water near the rim, it is natural that there the deltas were most quickly built and thus grew to largest size.

(2) Clapp remarks that in several cases the ice-contact slope extends clear around the sand plain, except on that side where there is higher ground. In some cases there is an approach to this in Lake Sudbury — e. g. the large Wayland plain, the Walden plain, and the sand plain which lies a mile due west from South Lincoln station; but as a rule about half the border of a delta in ice-contact and the rest is either definitely lobate or flattish, as where there was shallow water.

(3) Typical deltas in Lake Charles are said to be associated with effluent eskers on the south, marking the course of subglacial or superglacial outlets of the lakelets. The supposed connection of a number of lakelets by these streams accounts for the fact that although no two deltas are at exactly the same level, the discordance of their altitudes is slight. In the Sudbury valley, feeding eskers are common. Effluent eskers are rare. One which runs southward from the southeastern corner of Walden Pond connects the main Walden plain with the plain at Baker's Bridge. The plain one mile due west of South Lincoln station may have been enclosed by ice on all sides; for its southern

border is steep, and several effluent eskers extend out from it. These two cases, only, have been noted in Lake Sudbury as delta deposits which may well have been built in small ice-enclosed lakelets whose outlets on the southern side, through tunnels, perhaps, are marked by eskers. This condition of things, however, is the exception. The sand plains in nearly every case have well developed lobate borders on the southern side, which were clearly built not against an ice-wall, but in open water. Often they have been built forward so far as to nearly overlap the northern end of an older esker. This occurs, for instance, at the western end of the largest South Lincoln plain. Here, as is usual elsewhere, the margin of the plain is not continuous up to the head of the esker; there is a gap of a few hundred feet between the two. Instances have been noted (Woodworth) of cross-sections in sand plains which show where an esker abandoned by the withdrawal of the ice was subsequently buried by the forward extension of a sand delta. In a region where sand plains and eskers are abundant, this overlapping of eskers by deltas is almost inevitable. The mere topographical connection of the two sorts of deposits, therefore, does not prove that they were contemporaneous and that the "effluent" eskers mark outlets rather than inlets; unless as in the Walden plain, the border of the delta, near its junction with the esker, is an ice-contact rather than a lobate border. Aside from the two cases cited, there is nothing to suggest that the eskers in Lake Sudbury are other than feeding eskers. Frequently the eskers broaden out into gravel fans, at intervals, as is shown on the map. Some of these fans may well represent local lakelets in the much decayed ice; but I am inclined to think that as a rule even the fans are true ice-front deposits, built by successive stages at the continually receding mouth of a subglacial tunnel.

(4) "The elevation of all the plains of the system in this part of Lake Charles is very nearly or quite uniform, at about 150 feet above tide." (Clapp, c, 208). Clapp's own figures, however, place the range of discordance of altitudes at no less than 30 feet, — from 140 to 170 feet. This imperfect accordance of altitudes is thought to indicate a state of imperfect connection between the lakelets, by super- or subglacial streams.

Such an explanation whether correct or not, is certainly convenient. It might be successfully applied to any group of discordant sand plains, where the discordance amounts to even more than 30 feet. Recognizing, therefore, that this theory would account for the differences in delta levels in Lake Sudbury, one is tempted to ascribe all discordance there to a network of lakelets and decaying ice-blocks. The frequent occurrence of deltas with lobes at two or more levels favors this theory; moreover, the extraordinary case of the Saxonville plain has already been explained as due to the wasting of an abandoned ice-block in Lake Cochituate.

On the other hand, the remarkable way in which the many lobe altitudes fall into line, when plotted as in Plate 5, favors the idea that the discordance of levels, on the whole, is not irregular but systematic, — not so satisfactorily explained by isolated lakelets and wasting ice-blocks as by wide open lakes and an ice-front which lay essentially east and west.

Summary.

My conclusions from this study of the sand plains of the Sudbury valley are these: —

(*a*) In late glacial times the basin was occupied by a temporary ice-front lake.

(*b*) This lake underwent successive lowerings of level, in a manner that may be deduced after the horizontal step scheme. At each stage, deltas were built. In some cases, changes of level occurred while the delta was under construction, — notably in the Saxonville sand plain, because that was built forward from a huge ice-block which occupied part of Lake Cochituate long after the main ice-sheet had left it.

(*c*) Perhaps partly during the formation of the deltas — at any rate, after it — the whole region was tilted towards the south. By this tilting apparent confusion of altitudes of the deltas was brought about; but this discordance, when studied with proper accuracy and detail, is seen to be systematic. The tilt seems to be greatest in a due north-south direction, at the rate of about 7 feet per mile.

Further detailed work, in determining the altitudes of the best lobes of a great number of sand plains in the extinct lake basins, ought to demonstrate the truth or incorrectness of the tilting hypothesis. In view of the fact that tilting to some degree is almost certain, from evidence in other parts of glaciated North America and along the New England coast, and that even a short field study of the seemingly discordant deltas in the Sudbury valley goes far towards converting disorder into system, it appears that the grouping of sand plains in eastern Massachusetts may deserve even closer attention than it has usually received.

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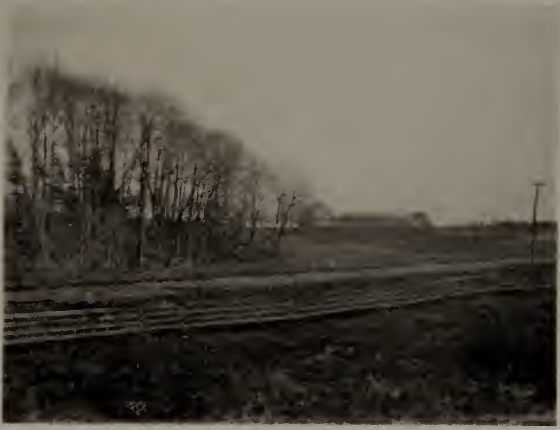
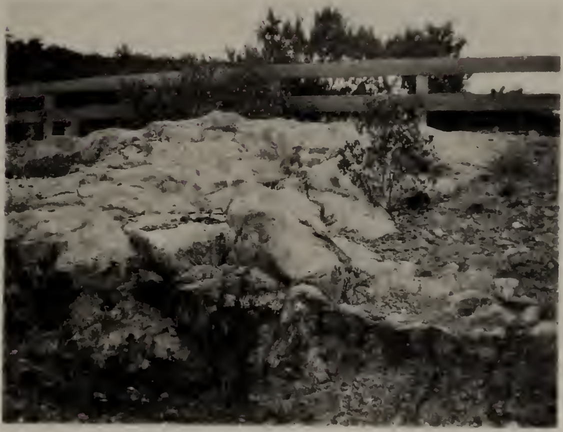
PLATE 1.

A. Lobate front of the big Saxonville delta, at its southwestern side. The three high lobes are about 170 feet in altitude, and probably belong to the Morseville water-plane. Just to the right of the house, and below it, is a lower lobe which belongs to one of the lower water-planes.

B. Water-worn surface of a ledge near Hobbs' Brook reservoir, mentioned on page 294. This may possibly record the work of a torrential outlet of Lake Sudbury.



A. LOBES SOUTH OF SAXONVILLE.



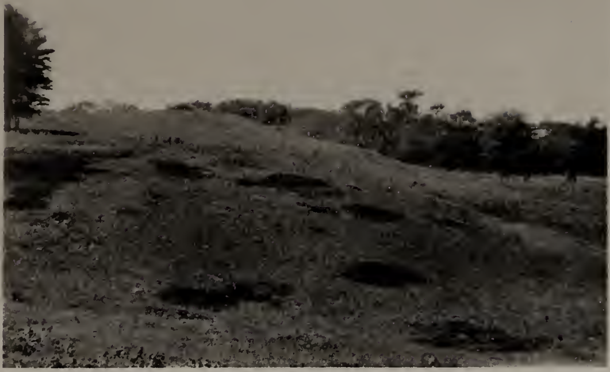
B. WATERWORN LEDGE NEAR HOBBS BROOK.

HELIOTYPE CO., BOSTON.

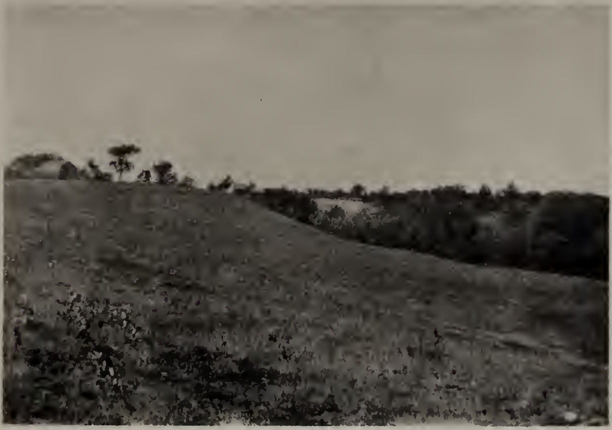
PLATE 2.

A. Double lobe-border of the big Saxonville delta at its northwestern corner (see pages 289 and 295). In the foreground is one of the low (137-foot) lobes, sloping down to the flood-plain of the Sudbury River, on the right, where horses are grazing. Beyond, in the centre of the picture, the doubly lobate front is seen in profile, — the higher 161-foot lobe sloping smoothly down to a 137-foot lobe.

B. Another view of the northwestern border of the Saxonville delta. The same 161-foot lobe is seen nearer than before; and part of the frontal slope of another lobe of the same group (165 feet) in the immediate foreground. On the right is the 137-foot terrace. Exactly in the centre on the picture, the intermediate (149-foot) lobe is very indistinctly shown in profile, occupying an interlobate hollow between the two higher lobes.



A. DOUBLE LOBE-BORDER NEAR SAXONVILLE.



B. LOBES NORTH OF SAXONVILLE.

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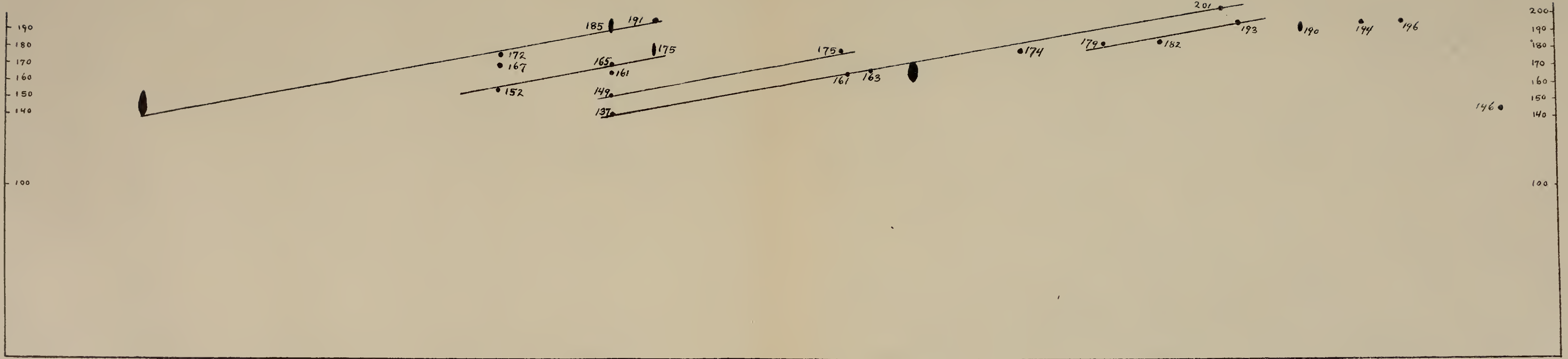
PLATE 3.

Tilted water-planes of Lake Sudbury. The significance of this diagram may best be seen by superposing it on Plate **4**, to which it is supplementary. It shows how the same points, plotted as in Plate **4**, might less perfectly be grouped into a series of more steeply tilted planes, which slant about 13 feet to the mile. (See page 295.)

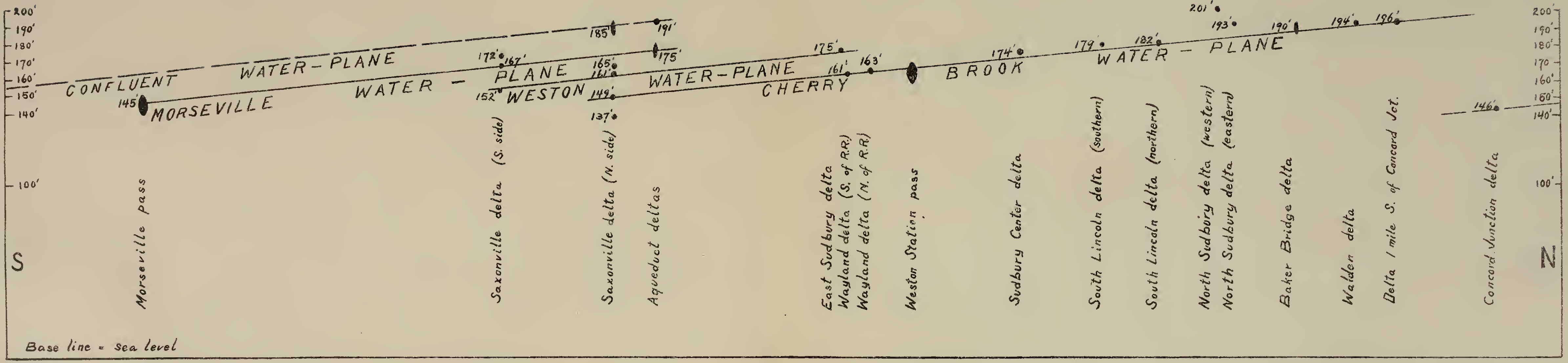
PLATE 4.

Tilted water-planes of Lake Sudbury. The altitudes of lobes and outlets, given on the map (Plate **5**), are plotted in profile, with reference to a north-south line. The points fall close to a series of planes which rise northward at the rate of about 7 feet to the mile. The horizontal scale is the same as in Plate **5**; vertical exaggeration about 75.



Tilted Water-Planes of Lake Sudbury.

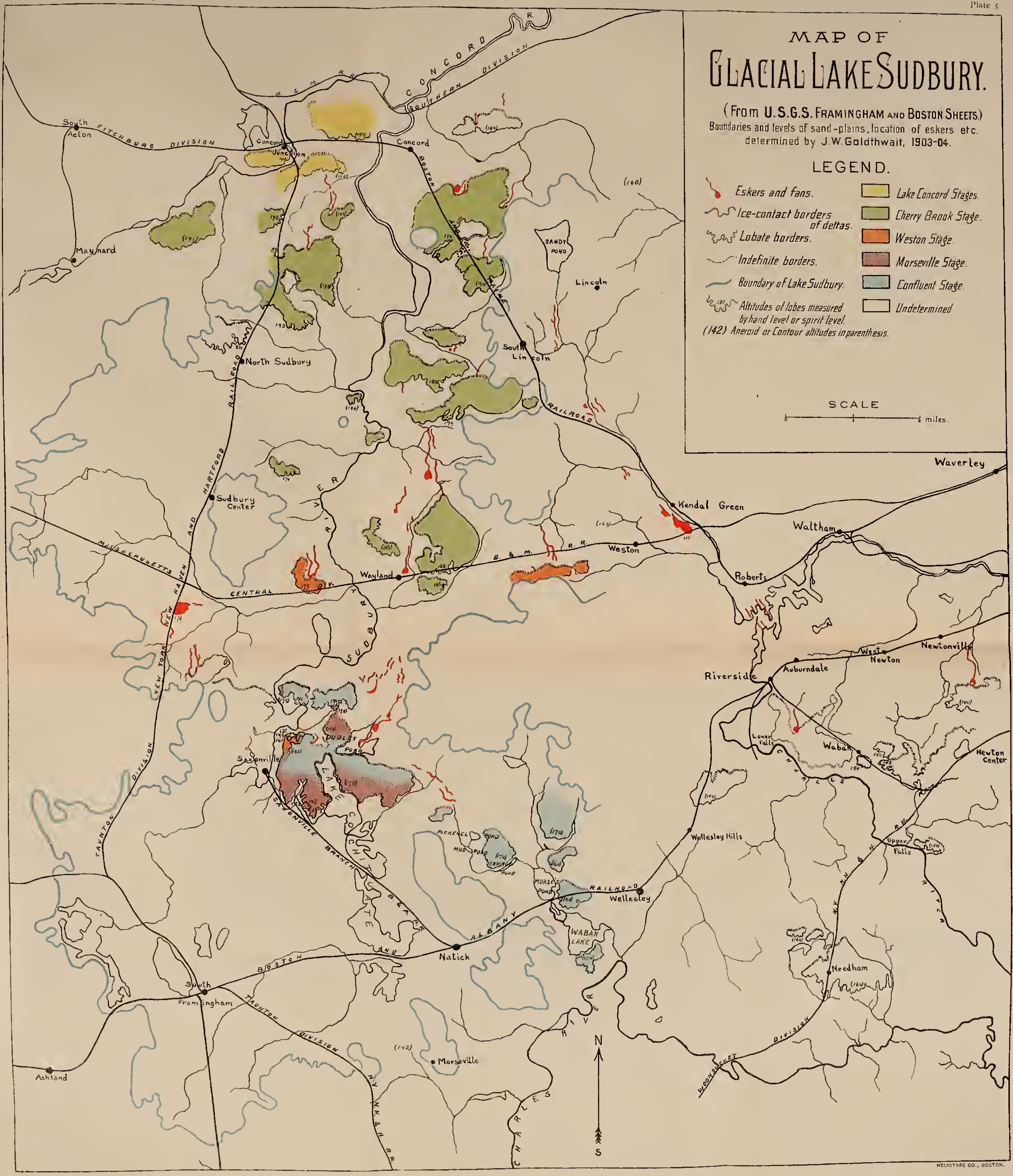
Plate 4.



Tilted Water-Planes of Lake Sudbury.

PLATE 5.

Map of Glacial Lake Sudbury, showing the probable boundary of the lake and the distribution of sand plains and eskers within its limits. The altitudes of lobes and of passes in the rim of the basin are given in feet (above mean low water, — Boston City base). The separation into groups, marking several successive water-planes, seems justifiable in view of the data presented in this paper, and summed up in Plate **4**.



MAP OF

GLACIAL LAKE SUDBURY.

(From U.S.G.S. FRAMINGHAM AND BOSTON SHEETS.)
Boundaries and levels of sand-plains, location of eskers etc.
determined by J.W. Goldthwait, 1903-04.

HELIOTYPE CO., BOSTON.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

E. EHLERS. The Annelids of the "Blake."
C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

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E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
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W. McM. WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
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S. J. HICKSON. The Antipathids.
HAROLD HEATH. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAUSTEDT. The Salpidæ and Doliolidæ.
H. B. WARD. The Sipunculids.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

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Vols. XLIII., XLVI., and XLVIII. of the BULLETIN, and Vols. XXV., XXVI., XXVII., XXX., XXXII., and XXXIII. of the MEMOIRS, are now in course of publication.

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Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Reports on the Scientific Results of the Expedition to the Eastern Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from October, 1904, to April, 1905, Lieut. Commander L. M. Garrett, U. S. N., Commanding.

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